Accuracy of Voxel-Based and Algebraic Formula-Based Methods in Quantifying Cerebral Aneurysm Volume by 3D-Rotational Digital Subtraction Angiography
An In-Vitro and In-Vivo Study

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Summary

Accurate knowledge of cerebral aneurysm volume would be valuable in guiding the volume of embolized material required for optimal filling of an aneurysm sac and recording percentage volume filling. Algebraic volumes are frequently estimated by algebraic volume formulae. 3D digital subtraction angiography (DSA) aids endovascular treatment planning and yields volumetric data. Our aim was to define the accuracy of 3D-DSA in quantifying aneurysm volume using an automated voxel-based volumetric method (voxel volume method) and compare results to volumes calculated by ellipsoid and cylindrical algebraic formulae (algebraic volume method).

We constructed 13 latex aneurysm moulds and measured their true volumes using a micropipette in-vitro. 3D-DSA was performed on contrast filled moulds and experimental volume estimated by both voxel and algebraic methods. In our in-vivo study we quantified the voxel and algebraic volumes from the 3D data sets of 75 cerebral aneurysms. The linear regression test provided correction values between voxel and algebraic methods.

The in-vitro study showed that the voxel volume method was the most accurate (mean percentage deviation from true volume $3.7 \pm 3.5\%$; $p = 0.9$). The ellipsoid method significantly underestimated $-11.2 \pm 13.6\%$; $p<0.05$) and the cylindrical method overestimated ($42.6 \pm 35.7\%$; $p<0.05$) true aneurysm volume. Similar results were obtained in-vivo. While algebraic measurements could be corrected by an equation, the clinical usefulness of this equation is questionable due to the large volume range to achieve a 95% confidence interval.

The voxel volume method is accurate in quantifying aneurysm volume. Aneurysms in-vivo do not conform to simple algebraic geometry. Aneurysm volume on 3D-DSA should be calculated by the voxel-based method and not by algebraic formulae.

Introduction

The importance of accurate measurement of cerebral aneurysm volume is that it can allow for more precise treatment planning and recording of treatment results in terms of packing density. If the total aneurysm volume is known, then the total volume of coils or filling material needed to achieve optimal aneurysm sac filling can be calculated and may improve long term angiographic stability. Packing densities < 20% have been shown to have a higher recurrence rate [1,2]. In addition, for aneurysms treated with liquid embolic polymers, accurate knowledge of the volume may be useful in reducing the risk of leakage of liquid embolic agents from overfilling of an aneurysm.

Endovascular treatment planning and execution is greatly aided by three dimensional (3D) digital subtraction angiography (DSA) [3,4]. Computed rotational angiography also yields quantitative information by reconstruction of the raw projection data into a volume dataset [5,6]. This allows the volume of the aneurysm to be calculated by an automated voxel-based volumetric analysis of the opacified aneurysm using dedicated software. Aneurysm volumes are often quantified using simple algebraic equations based on the assumption they have regular geometry; however, aneurysms in-vivo do not conform to simple geometric shapes but possess complex geometry. The accuracy of 3D digital subtraction angiography (DSA) for measuring aneurysm volume using these methods has not been defined. Our aim was to characterize the performance of 3D DSA in quantifying aneurysm volume by measuring the opacified aneurysm's voxel volume. We termed this method of volume estimation the 'voxel volume method'. We compared this method to standard assessment by algebraic volume formulae. Our study was composed of an in-vitro model, with a follow-up in-vivo study.

Material and Methods

Preparation of aneurysms

Using 3D angiographic projections of 13 aneurysms, we made anatomically realistic moulds of these aneurysms by standard clay modelling techniques with air hardening modelling clay. After setting, we applied a uniform layer of concentrated liquid latex to the mould and allowed it to dry for six hours. This embossing process was repeated until a thickness of 3 mm was obtained, before demoulding. We used a micropipette with a mean error of $<0.8\%$ to measure the volume of the aneurysms. We filled the latex aneurysm moulds with iodinated contrast medium until a convex meniscus of fluid was produced. We used a 70% concentration of 300 mg/ml of iodinated contrast medium, as this is the concentration we routinely use in our clinical practice. We repeated this procedure five times, and took the average as the definitive volume.

Angiographic data were acquired on an Advantx LCV plus DSA system (GE Medical Systems, Buc, France) using the rotational angiographic technique. We constructed a head phantom from a real human skull filled with minced meat to simulate the bone and soft tissue of a normal cranium. We placed the latex aneurysm sac in the soft tissue with the neck superiorly, and then covered the top of the neck with a cap of further simulated soft tissue. The model was positioned in the isocenter of the x-ray source and the image intensifier. The data acquisition consisted of two rotations. The first rotation acquires the mask images and was performed over a 200 degree arc at a rotation speed of 40 degrees/s providing 44 projections on a matrix size of 512 x 512 pixels. The c-arm then rotates back at 30 degrees/s to the starting point. During this c-arm reversal, the soft tissue cap covering the neck of the aneurysm was removed, the aneurysm filled manually with the micropipette to its definitive volume, and the soft tissue cap replaced. The second data acquisition rotation acquires the opacified images and was performed with the same c-arm parameters and direction as for the mask run. The total time between the start of the c-arm reversal rotation and the beginning of the image run was eleven seconds. The X-ray acquisition parameters were as selected from standard practice: 120kV and 250mA. The source to image distance was 120 cm, the image intensifier diameter was 32 cm with a field of view of 23 cm and the focal spot 0.6 mm.

After acquisition, the direct data was corrected for pincushion and S distortion of the imaging system with the aid of data sets derived from weekly calibration data using a grid phantom. The conic projection geometry of the C-arm was computed with weekly calibration data from a Helix phantom (GE Medical systems) [7]. Following correction of the data, the 44 mask and 44 contrast images of each aneurysm were post-processed on a dedicated workstation, Advantage Windows 3.1 and Advantage 3D-XR 2.0 (GE Medical Systems). We used a 3D-reconstruction algorithm based on the algebraic reconstruction technique to generate a volume dataset from the projection data.

Quantification of aneurysm volume by 3D DSA in-vitro

Voxel volume method

3D-reconstructions of the data were visualised by maximum intensity projection (MIP) using optimal windows and surface-shaded-dis-

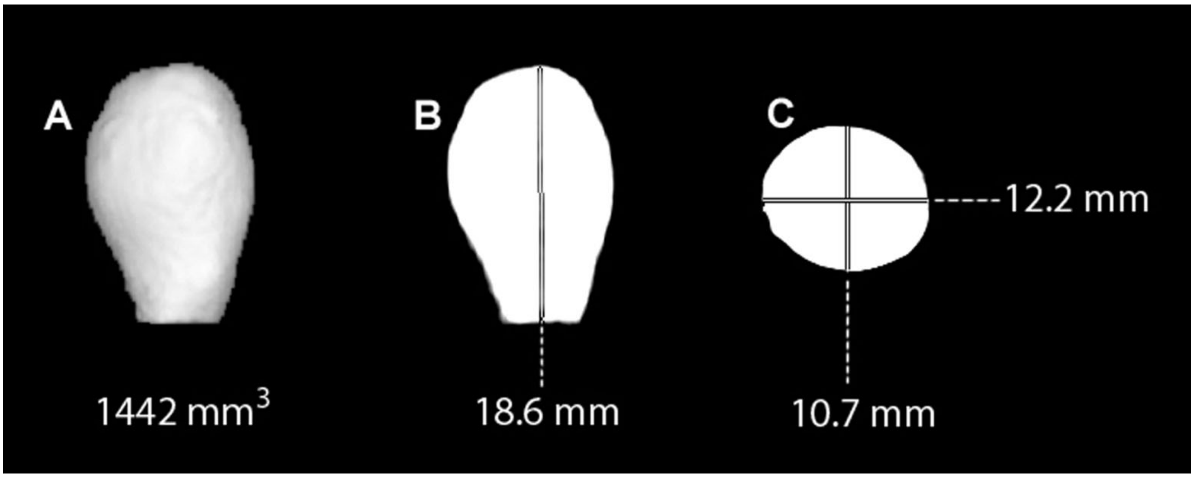

Figure 1 Representative images from an experimental aneurysm. A) shows the 3D SSD of the aneurysm with a voxel volume measuring 1442 mm^3. B,C) are MIP images showing the length, width and height of the aneurysm in mm. From these 2D measurements the ellipsoid and cylindrical volumes are calculated by algebraic formulae (1271 mm^3 and 2174 mm^3 respectively in this example). The true volume of this experimental aneurysm measured using a micropipette is 1410 mm^3.

play (SSD) using optimal threshold for each experimental aneurysm.

The optimal threshold of the SSD image was appreciated as a reference of the MIP image. As each of the aneurysm moulds was filled to its predetermined true volume with the micropipette, no additional manipulation of the volume was required (e.g. use of the electronic scalpel to remove part of the 3D volume) prior to volume assessment. Images were reconstructed by a neuroradiologist (N.F.F.) experienced in 3D imaging. We calculated the volume of each experimental aneurysm using dedicated software on the workstation.

This calculates the volume by multiplying the total number of voxels belonging to the opacified aneurysm by the corresponding voxel volume (0.3 mm3 for the 23 cm field of view used) (figure 1).

Algebraic volume method

Cerebral aneurysm volume is often approximately calculated on the assumption that aneurysms possess regular geometric shapes [8-10]. We assessed aneurysm volumes using algebraic formulae based on the supposition that aneurysms are either ellipsoid [$Ve = (4/3)\ \pi\ (a/2)\ (b/2)\ (c/2)$] or cylindrical [$Vc = \pi\ (a/2)\ 2(b)$] where Ve represents ellipsoid aneurysm volume, Vc, cylindrical aneurysm volume; a, width; b, length; c, height of the aneurysm (figure 1). The volume of multilobed aneurysms was calculated as the sum of their individual components.

Quantification of aneurysm volume by 3D DSA in-vivo

We next quantified aneurysm volumes form the 3D DSA data sets of 52 patients with 75 cerebral aneurysms. To extract the aneurysm from its parent vessel in-vivo, we used a combination of optimal thresholding and the electronic scalpel to cut away parts of the 3D volume leaving the aneurysm alone as the region of interest. Aneurysm volume was assessed by both the voxel and algebraic methods as described above.

Packing ratios based on voxel and algebraic aneurysm volumes

We determined the packing ratio of 60 of the in-vivo aneurysms. The packing ratio was calculated for each aneurysm by taking the sum of the volumes of all the coils introduced divided by the aneurysm volume. The aneurysm volume was already calculated by the voxel and algebraic volume methods as described above. The volume of an introduced coil was calculated on the supposition that coils are cylindrical by the following formula: $Vcoil = \pi\ (d/2)\ 2(l)$ where Vcoil represents volume of coil; d, diameter of coil; and l, length of coil. The primary diameter of each type of coil we used is available from Boston Scientific (Fremont, CA) and Microvention (Aliso Viejo, CA). Packing ratios based on calculation of aneurysm volumes by the voxel and algebraic methods were determined.

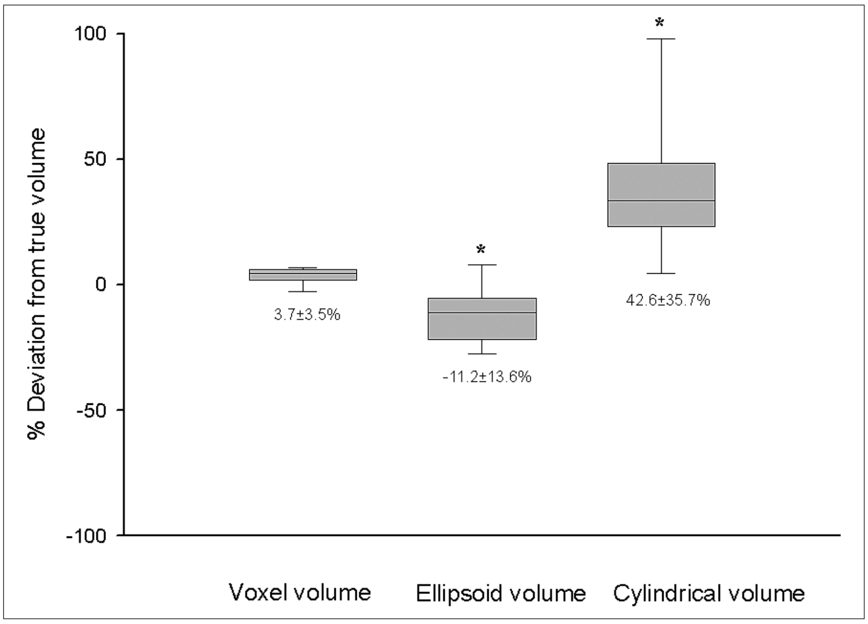

Figure 2 Box-and-whisker plot of the in-vitro aneurysm volume data. The central box represents values from the 25^{th} to 75^{th} percentile. The line in the box denotes the median value. The top and bottom of the whisker gives the 5^{th} and 90^{th} percentiles respectively. The numbers beneath the box-and-whisker plot are the mean ± standard deviation. The plot shows that the voxel volume method is the most accurate method for assessing aneurysm volume with the ellipsoid method significantly underestimating and the cylindrical method significantly overestimating true aneurysm volume. The asterix (*) indicates $p < 0.05$ for the ellipsoid and cylindrical volume methods versus the true and voxel volume methods.

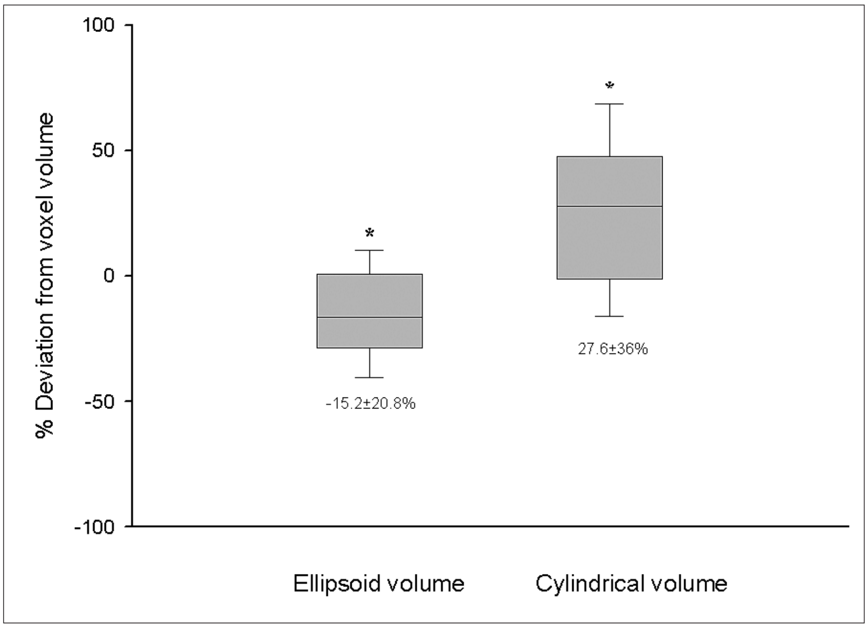

Figure 3 Box-and-whisker plot of the in-vivo aneurysm volume data. The components of the box-and-whisker plot are as described in figure 1. The numbers beneath the box-and-whisker plot are the mean ± standard deviation. The plot shows that the ellipsoid method significantly underestimates and the cylindrical method significantly overestimates aneurysm volume. The asterix (*) indicates $p < 0.05$ for the ellipsoid and cylindrical volume methods versus the voxel volume method.

Statistics

The Wilcoxon Rank Sum Test for non-parametric data was used to determine the accuracy (the difference between calculated and actual volumes) of the voxel and algebraic volume methods. The correlation between different methods of measuring aneurysm volume was determined by Pearson's test. Correction values for the in-vivo study were obtained by the linear regression test, having as the fixed matrix, the voxel volume values and as the variable matrix, ellipsoid and cylindrical volumes. The level of statistical significance was $p \leq 0.05$.

Results

In-vitro study

Results showed that the voxel volume method was the most accurate method for assessing aneurysm volume (mean percentage difference from true volume 3.7 ± 3.5%, p = 0.094) (figure 2). The mean volume of the 13 aneurysm moulds was 972 mm^3 (range 156 – 2960 mm^3). The ellipsoid method significantly underestimated the true aneurysm volume (mean percentage difference from true volume -11.2 ± 13.6%; $p < 0.05$), with the cylindrical method significantly overestimating the true aneurysm volume (42.6 ± 35.7%, $p < 0.05$) (figure 2). Similar results were obtained when the algebraic method was compared to the voxel method, with the ellipsoid method underestimating (-14.6 ± 12.7%, $p < 0.05$) and the cylindrical method overestimating (36.9 ± 32.3%, $p < 0.05$) voxel aneurysm volume.

In-vitro study

In the in-vivo study the voxel volume method was used as the gold standard and compared to the algebraic volume method (figure 3). The mean volume of the 75 aneurysms was 165 mm^3 (range 10 – 1571 mm^3). While the correlation values between the voxel volume and algebraic methods were good (r = 0.96 for ellipsoid, r = 0.95 for cylindrical versus voxel methods), the ellipsoid method significantly underestimated aneurysm volume (mean percentage difference from voxel volume -15.2 ± 20.8%, $p < 0.001$), with the cylindrical method significantly overestimating aneurysm volume (27.6 ± 36%, $p < 0.001$). Using the voxel volume method for calculating aneurysm volume, the packing ratio was 40.9%. The ellipsoid volume method significantly overestimated the mean packing ratio (51.1%, mean percentage overestimation 24.2%, $p < 0.001$) and the cylindrical method significantly underestimated the mean packing ratio (34.8%; mean percentage underestimation -14.8%, $p < 0.001$) (table 1).

The correction values for conversion of ellipsoid and cylindrical volumes to voxel volumes can be expressed by the linear equation as follows: voxel volume = 16.5 + (0.99 × ellipsoid volume), with a 95% confidence interval of ± 78 µl and voxel volume = 54.0 + (0.47 × cylindircal volume), 95% confidence interval of ± 137 µl.

Discussion

The main finding of this study is that algebraic methods should not replace the more accurate voxel volume method for aneurysm volume assessment using 3D DSA techniques. While the correlations between voxel volume and algebraic methods are good, the ellipsoid method, on average, underestimates aneurysm volume and overestimates packing ratios with the opposite being true for the cylindrical method. Also, it was shown that the correction of algebraic values with an equation is possible, but for a 95% confidence interval the range is relatively large and, especially for small aneurysms, unlikely to be clinically useful.

There are a variety of methods available to assess aneurysm volume by rotational DSA. Various algebraic formulae have been proposed to quantify cerebral aneurysm volume, including ellipsoid and cylindrical formulae [8-10]. The premise that intracerebral aneurysms have regular definable geometry is clearly incorrect. Intracerebral aneurysms in-vivo are irregular with complex geometry. The voxel volume method calculates aneurysm volume using dedicated software on the workstation. The small voxel size allows for high spatial resolution with accurate morphologic delineation and assessment of the total number of voxels belonging to the contrast filled aneurysm.

In an in-vitro model, Piotin et Al calculated the volume of a single epoxy aneurysm mould by 3D DSA, MR angiography and CT angiography [11]. Using the voxel volume method, they found that 3D-DSA was the most accurate with a 7% overestimation of the true volume. In our in-vitro study we performed measurements on 13 aneurysm moulds. The use of a micropipette allowed very accurate measurement of the true volume of the in-vitro aneurysms. As the micropippetted volume was the volume added to the aneurysm during 3D acquisition, this allowed an accurate and reproducible method to assess the performance of 3D DSA. Because we were dealing with a rigid non-pulsatile model, partial volume effects due to pulsatile motion, patient movement and non stationary opacification were not accounted for, factors which may reduce the level of accuracy of 3D DSA in-vivo. In our phantom model, the voxel volume method was most accurate with an absolute error of within 4% of the true volume (figure 2). The algebraic method of volume estimation yielded a significant error, with the ellipsoid volume method significantly underestimating and the cylindrical method significantly overestimating the true volume. However, in the algebraic method there was a large standard deviation, highlighting that this method can significantly over- or underestimate the volume of an individual aneurysm depending on the shape of the aneurysm in question (figure 2).

Table 1 **Comparison of aneurysm packing density based on volume estimation by the voxel, ellipsoid and cylindrical method**

	Voxel volume	Ellipsoid volume	Cylindrical volume
Percentage packing density	40.9	51.1	34.8
Mean % error of algebraic Vs voxel method	24.2	-14.8	
P value	<0.001	<0.001	

Our in-vivo study sought to address some of the limitations of our in-vitro study by comparing the voxel and algebraic volume methods in 75 cerebral aneurysms following 3D DSA acquisition in-vivo. As our in-vitro data showed that the voxel volume method was the most accurate, this method was used as the reference volume for the in-vivo study. We found similar results to the in-vitro study, with the ellipsoid volume method significantly underestimating and the cylindrical method significantly overestimating the volume (figure 3).

In addition, as aneurysm volume is the denominator in the equation to assess packing density (packing density = total coil volume / aneurysm volume), not surprisingly we found that the ellipsoid method significantly overestimated and the cylindrical method significantly underestimated packing density (table 1). There was a large standard deviation in calculating aneurysm volume by the algebraic method indicating that the algebraic method may not be accurate in assessing the volume of an individual aneurysm. This is reflected by the finding that while the ellipsoid and cylindrical volumes could be corrected by a linear equation, for a 95% confidence interval the volume range is relatively large and unlikely to be of use in clinical practice.

Conclusions

Cerebral aneurysms do not conform to simple geometric shapes. The voxel volume method is the most accurate method for calculating aneurysm volume by 3D DSA. There is a significant error with the use of simple geometric formulae to calculate aneurysm volume. Correction equations to convert geometric to voxel volumes do not appear sufficiently accurate to be of use clinically. Quantifying aneurysm volume, and thus packing density, should be performed by 3D DSA with dedicated software to calculate the voxel volume of an aneurysm and not by the use of algebraic formulae.

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